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Marchok et al.

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[45] Date of Patent: Aug. 4, 1998

[54] **MULTI-POINT OFDM/DMT DIGITAL COMMUNICATIONS SYSTEM INCLUDING REMOTE SERVICE UNIT WITH IMPROVED RECEIVER ARCHITECTURE**

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[73] Assignee: **Tellabs Operations, Inc.**, Lisle, Ill.

[21] Appl. No.: **700,779**

[22] Filed: **Aug. 22, 1996**

[51] **Int. Cl.**[6] **H04J 11/00**

[52] **U.S. Cl.** **370/208**; 375/316; 375/260; 370/210

[58] **Field of Search** 370/204, 206, 370/208, 210, 211; 375/344, 338, 316, 260; 455/192.2, 202, 257

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"Cablespan 2300", Training Presentation, Tellabs, Inc., 1996.

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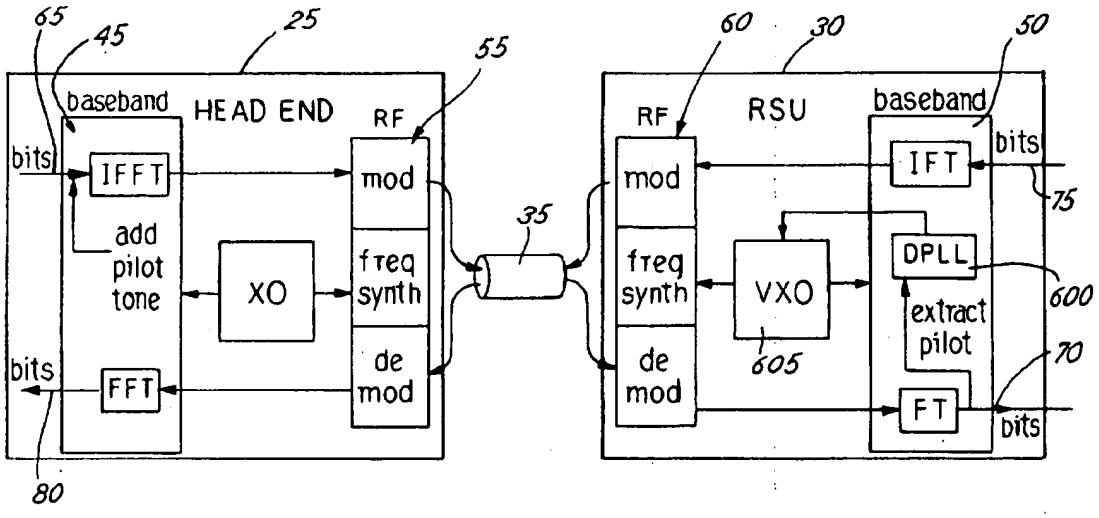
Assistant Examiner—A. Bnimoussa
Attorney, Agent, or Firm—McAndrews, Held & Malloy, Ltd.

[57] **ABSTRACT**

A multi-point communications system is set forth. The communications system comprises a primary transmitter disposed at a primary site and a plurality of receivers respectively disposed at a plurality of secondary sites. The primary transmitter generates OFDM/DMT transmissions over a first number of transmission bins to transmit communication data in those bins. A transmission medium is used for transmitting the OFDM/DMT transmissions from the primary transmitter at the primary site to the plurality of receivers disposed at a plurality of secondary sites. Each of the plurality of receivers employs a unique receiver architecture that digitally processes exclusively a reduced subset of the first number of bins transmitted by the primary transmitter to recover communication data that is transmitted in the reduced subset of the first number of bins. Such a receiver architecture eliminates much of the complexity typically associated with receiving and processing a wideband OFDM/DMT signal, thereby making the communications system subject to economical and practical implementation in applications having receivers respectively located at a large number of secondary sites.

20 Claims, 13 Drawing Sheets



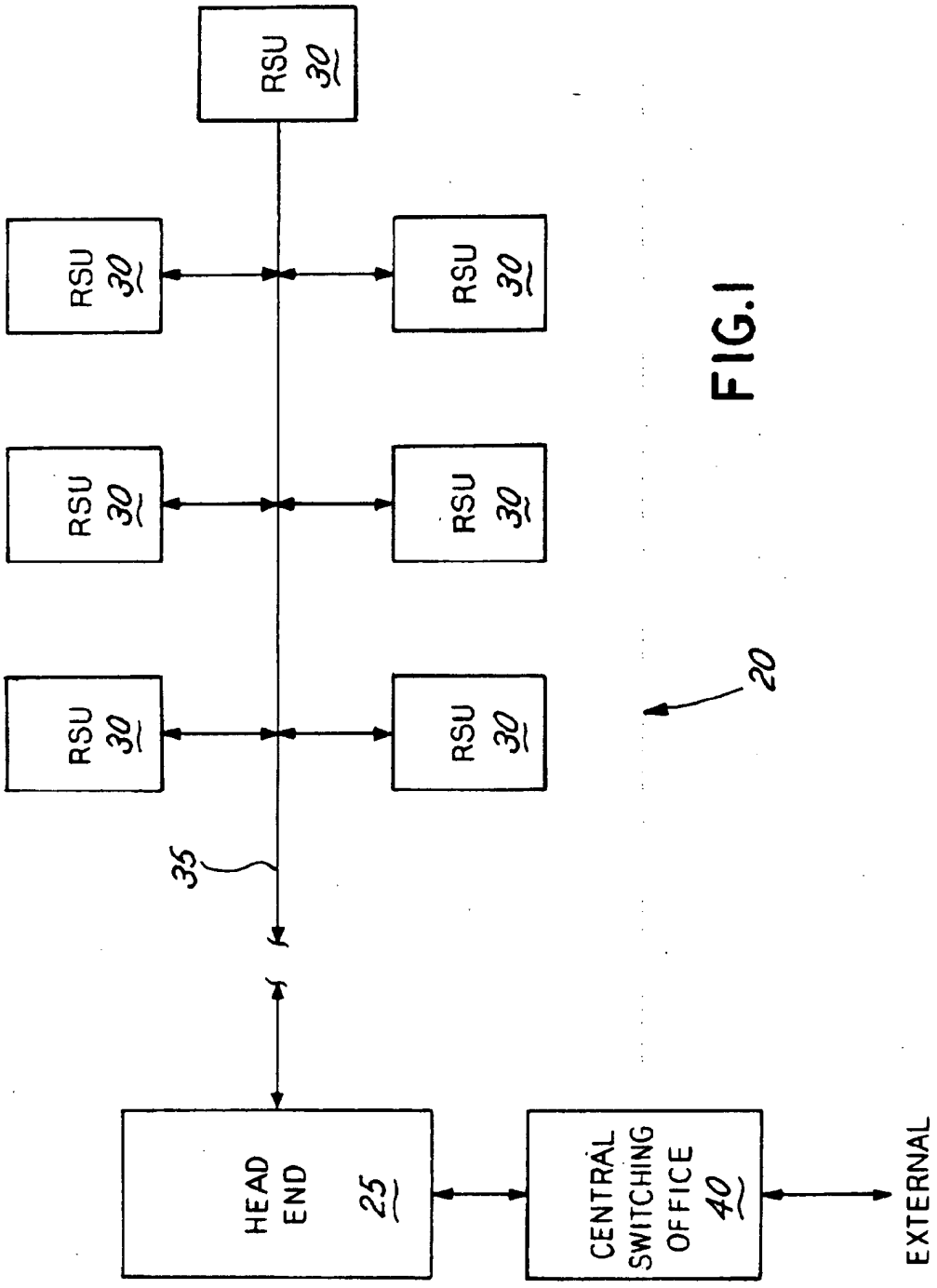

RSU 30
RSU 30
RSU 30
RSU 30
RSU 30
RSU 30
RSU 30
20
35
HEAD END 25
CENTRAL SWITCHING OFFICE 40
EXTERNAL

FIG.1

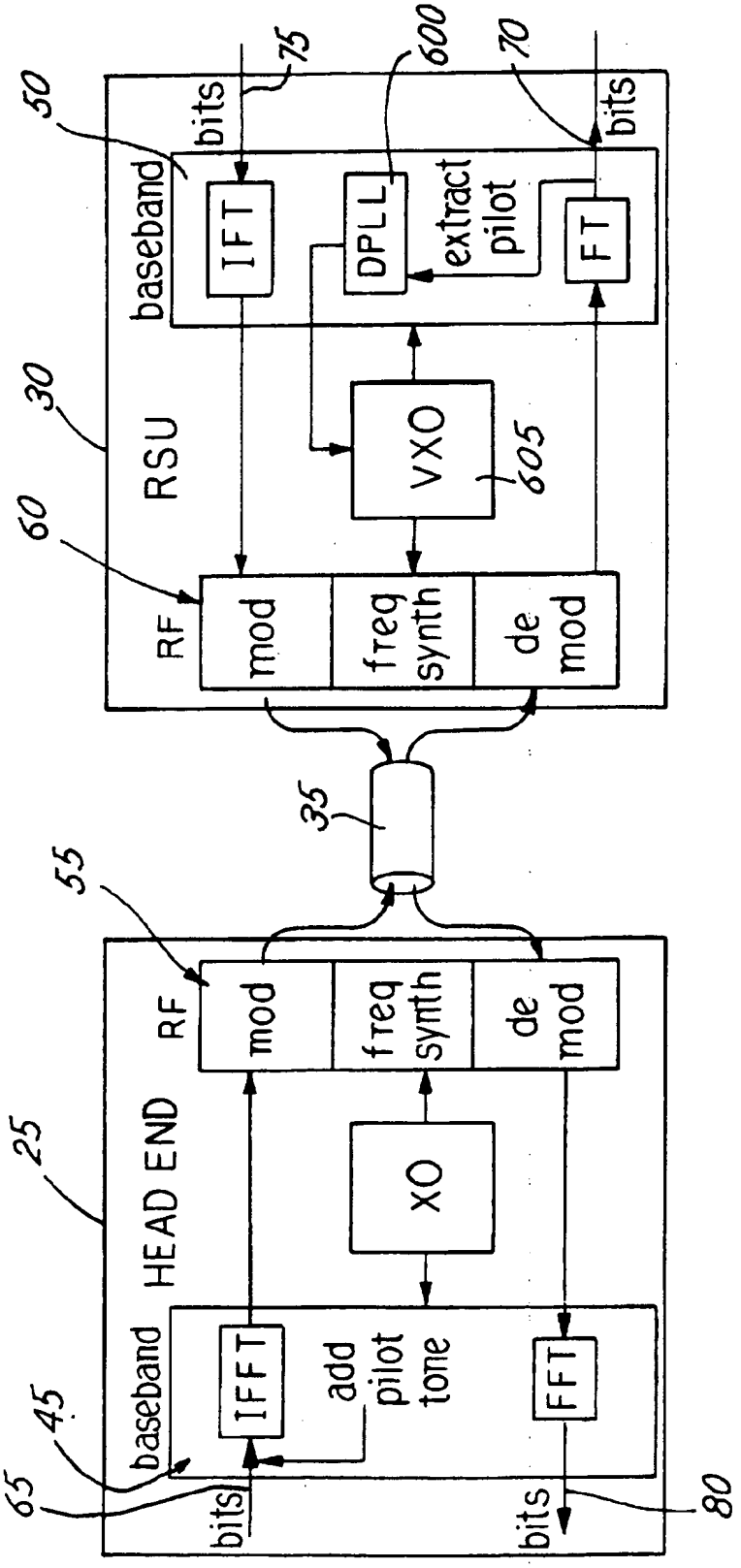

50
baseband
bits
75
IFT
600
DPLL
extract pilot
70
FT
bits
30
RSU
VXO
605
60
RF
mod
freq synth
de mod
35
55
RF
mod
freq synth
de mod
25
HEAD END
XO
baseband
IFFT
add pilot tone
FFT
45
65
bits
bits
80

FIG. 2

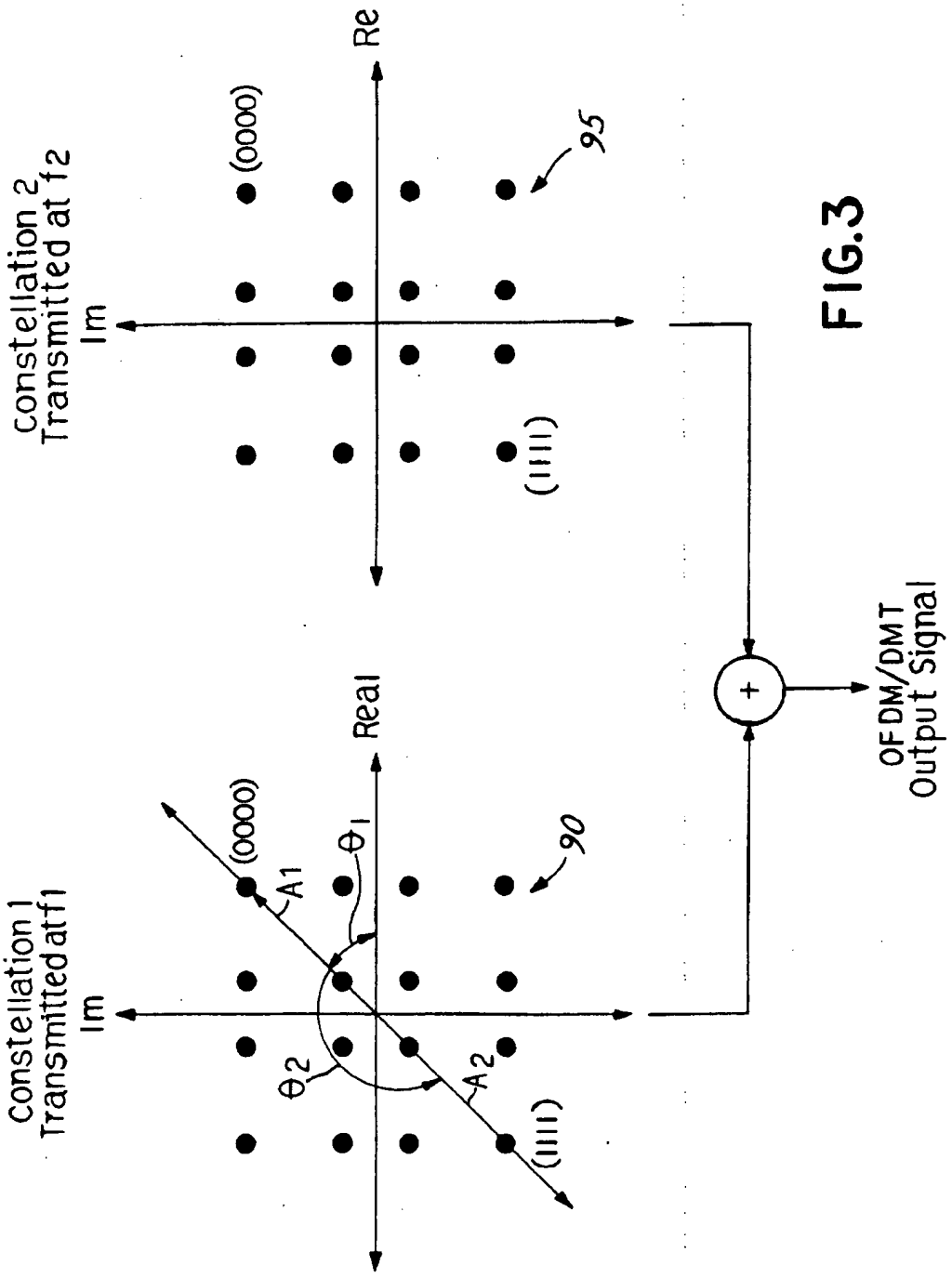

Constellation 2
Transmitted at f2
Im
Re
(0000)
(1111)
95
Constellation 1
Transmitted at f1
Im
Real
(0000)
(1111)
θ1
θ2
A1
A2
90
+
OFDM/DMT
Output Signal

FIG.3

FIG. 4

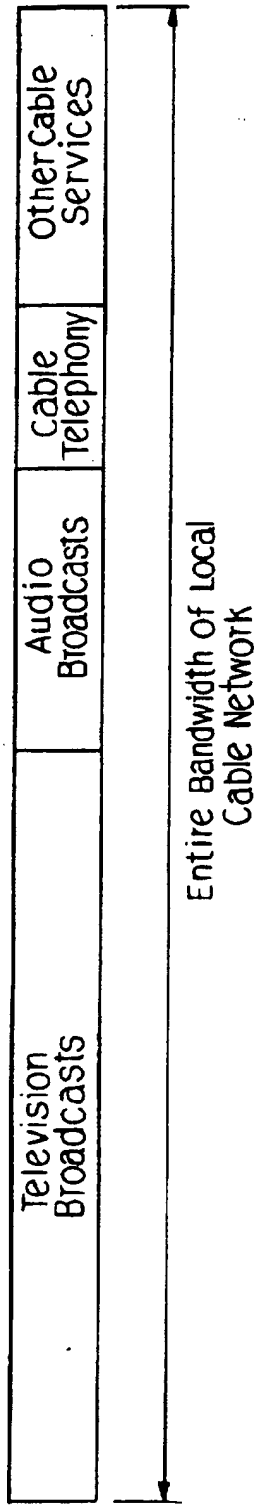

Television Broadcasts
Audio Broadcasts
Cable Telephony
Other Cable Services
Entire Bandwidth Of Local Cable Network

FIG. 5

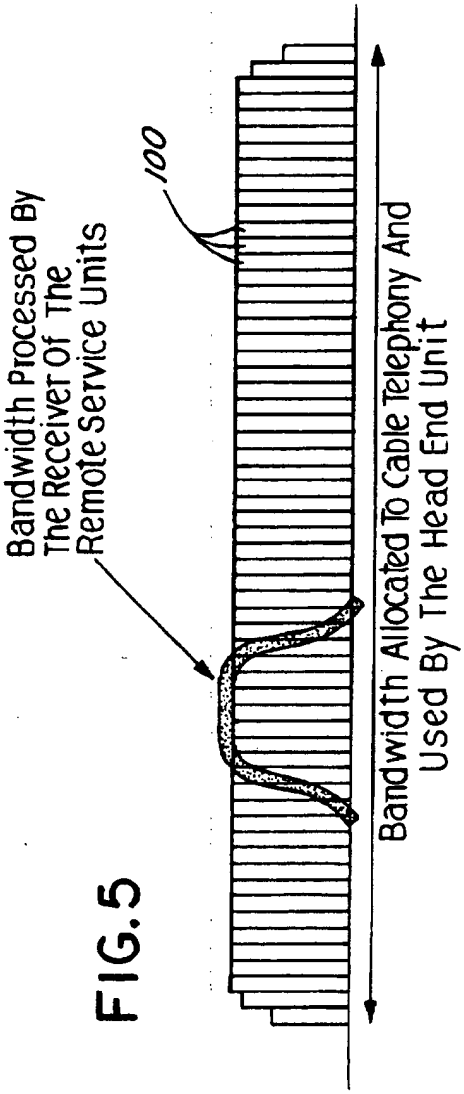
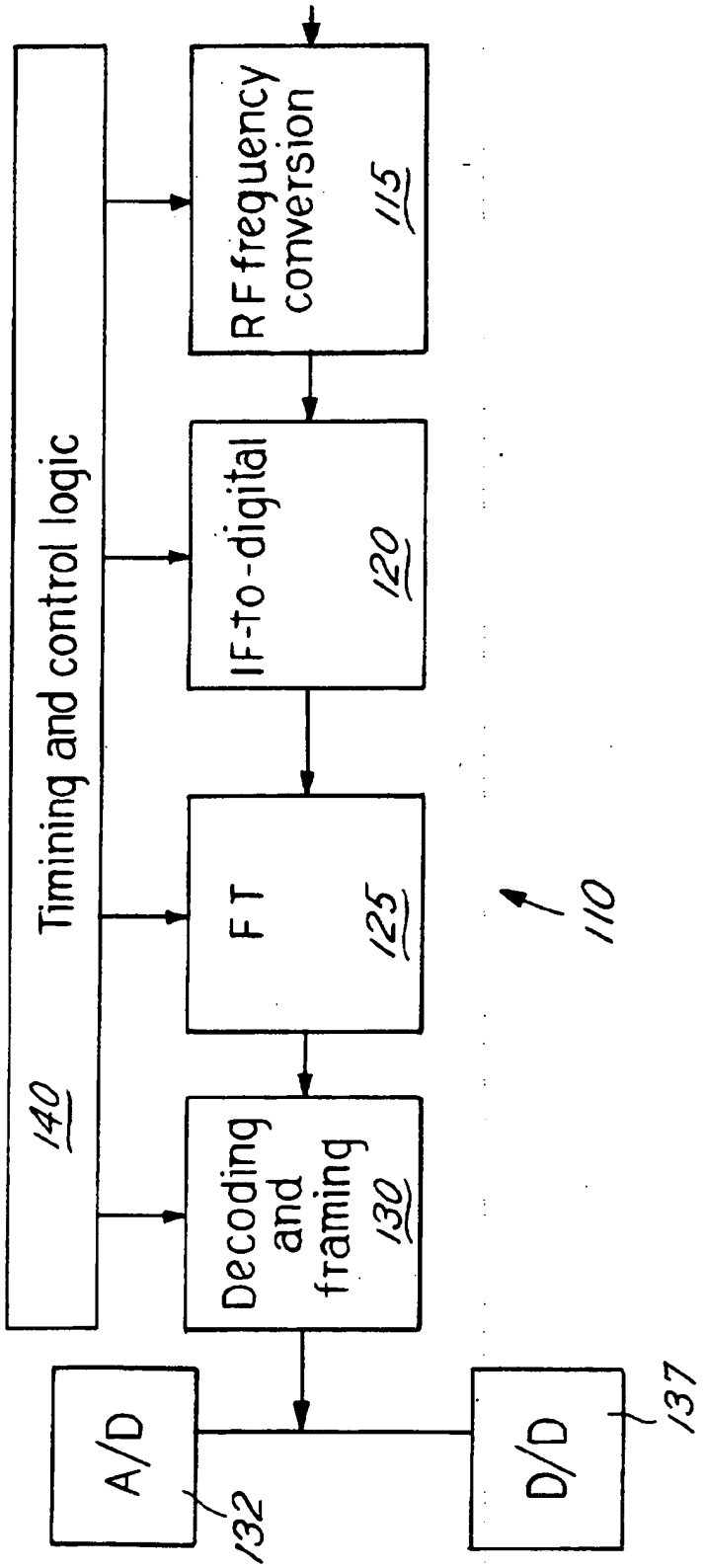

Bandwidth Processed By The Receiver Of The Remote Service Units
100
Bandwidth Allocated To Cable Telephony And Used By The Head End Unit

FIG.6


RF frequency conversion
115
IF-to-digital
120
FT
125
Decoding and framing
130
A/D
132
D/D
137
Timining and control logic
140
110

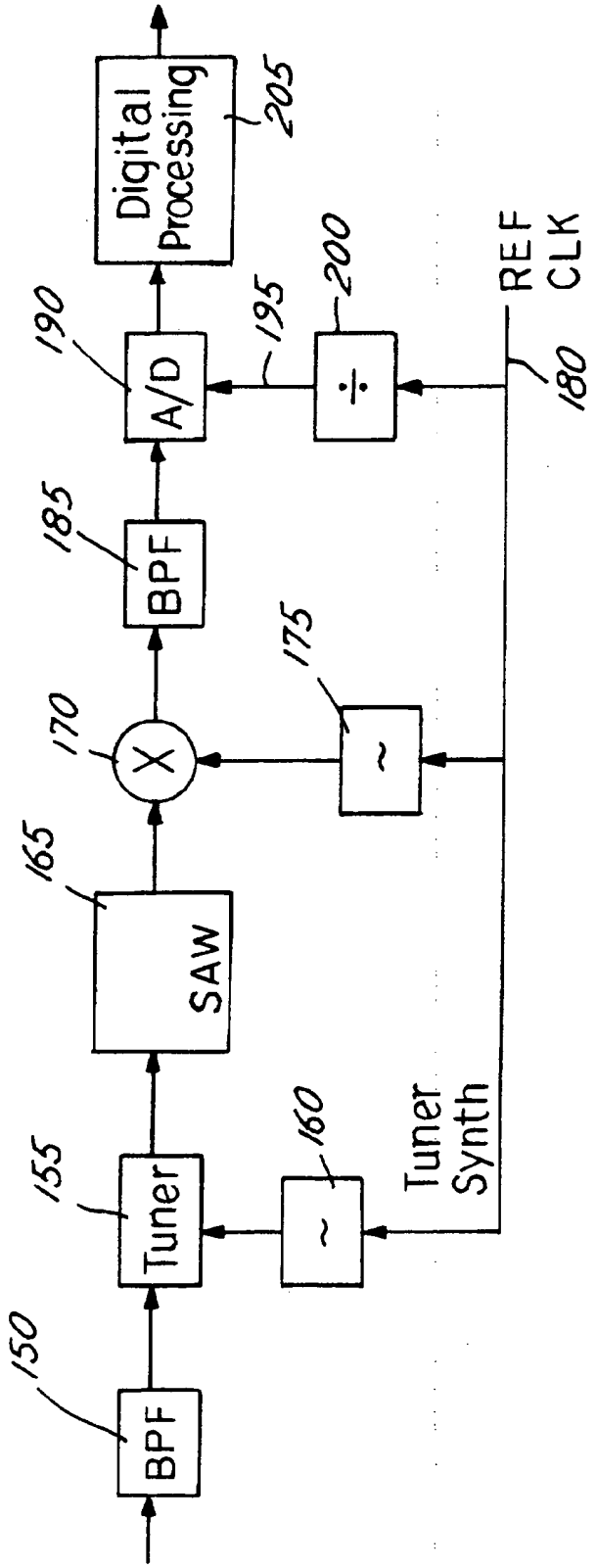

Digital Processing
205
A/D
190
÷
200
195
REF CLK
180
BPF
185
~
175
X
170
SAW
165
Tuner
155
~
160
Tuner Synth
BPF
150

FIG. 7

FIG.8

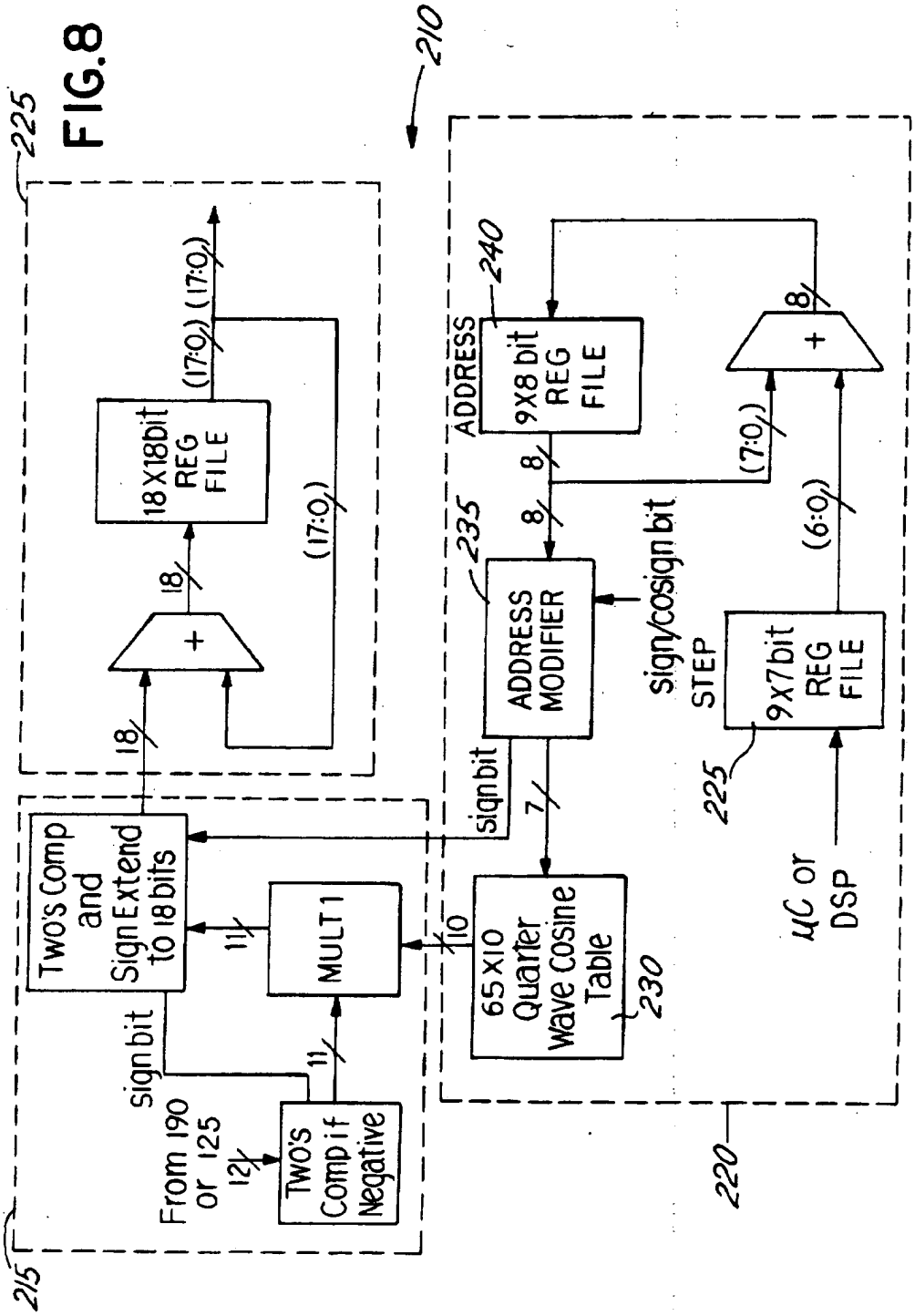

210
225
18X18bit REG FILE
(17:0)
(17:0)
(17:0)
18
+
18
ADDRESS
240
9X8 bit REG FILE
8
8
(7:0)
+
8
235
ADDRESS MODIFIER
sign/cosign bit
STEP
9X7bit REG FILE
(6:0)
225
sign bit
7
Two's Comp and Sign Extend to 18 bits
11
MULT 1
10
65 X10 Quarter Wave Cosine Table
230
μC or DSP
sign bit
11
From 190 or 125
12
Two's Comp if Negative
215
220

FIG. 9

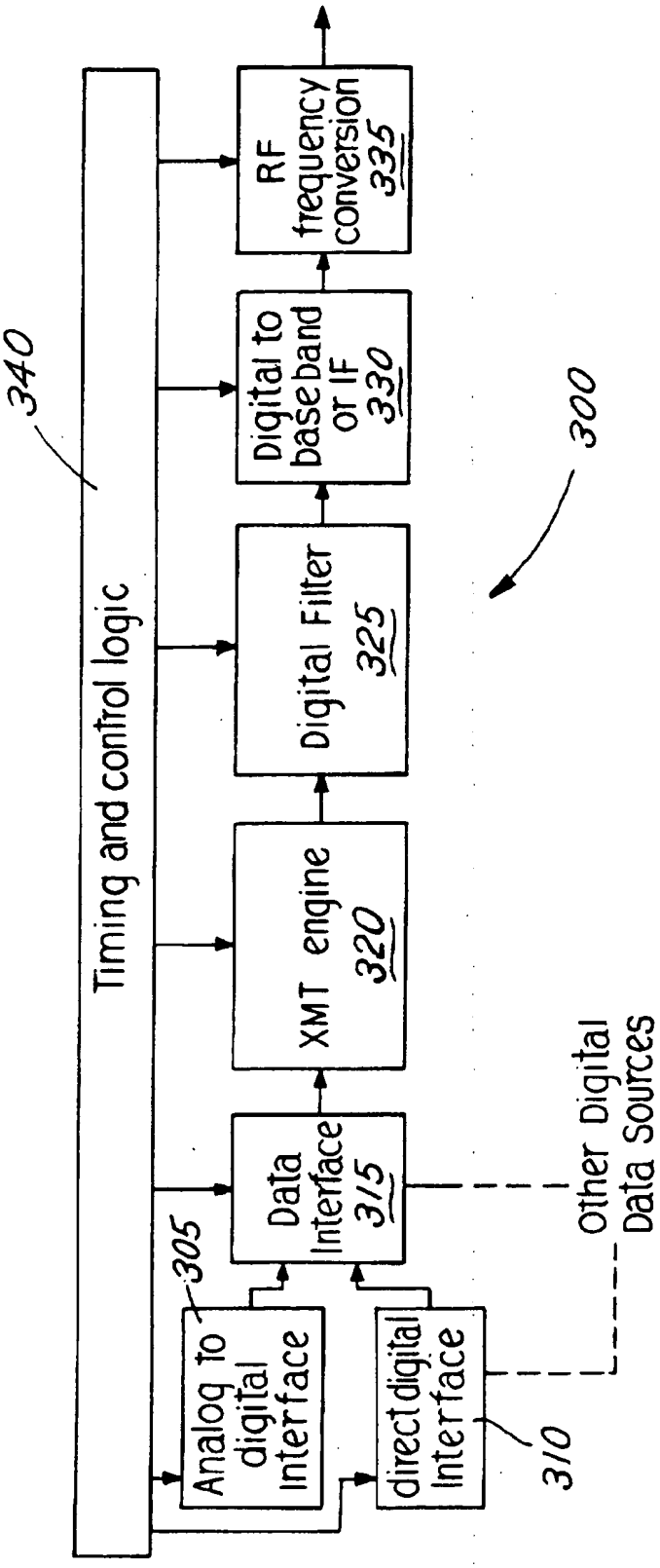

Timing and control logic
340
300
RF frequency conversion 335
Digital to baseband or IF 330
Digital Filter 325
XMT engine 320
Data Interface 315
305
Analog to digital Interface
direct digital Interface
310
Other Digital Data Sources

FIG. 10

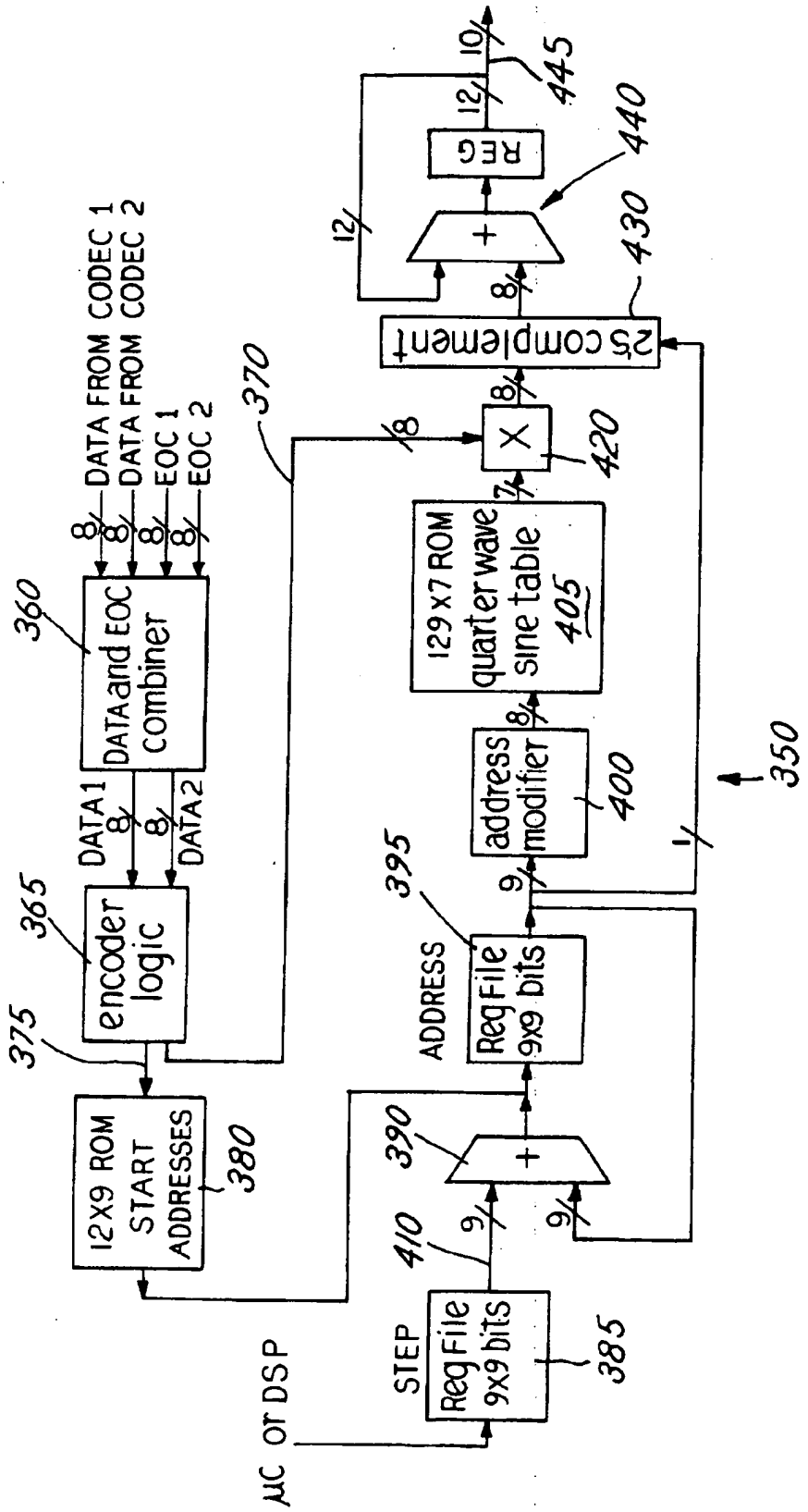

DATA FROM CODEC 1
DATA FROM CODEC 2
EOC 1
EOC 2
DATA and EOC combiner
360
DATA1
DATA2
encoder logic
365
375
12X9 ROM START ADDRESSES
380
µC or DSP
STEP
Reg File 9x9 bits
385
410
390
ADDRESS
Reg File 9x9 bits
395
address modifier
400
129 x 7 ROM quarter wave sine table 405
X
420
370
2's complement
430
REG
440
445
350

FIG.11

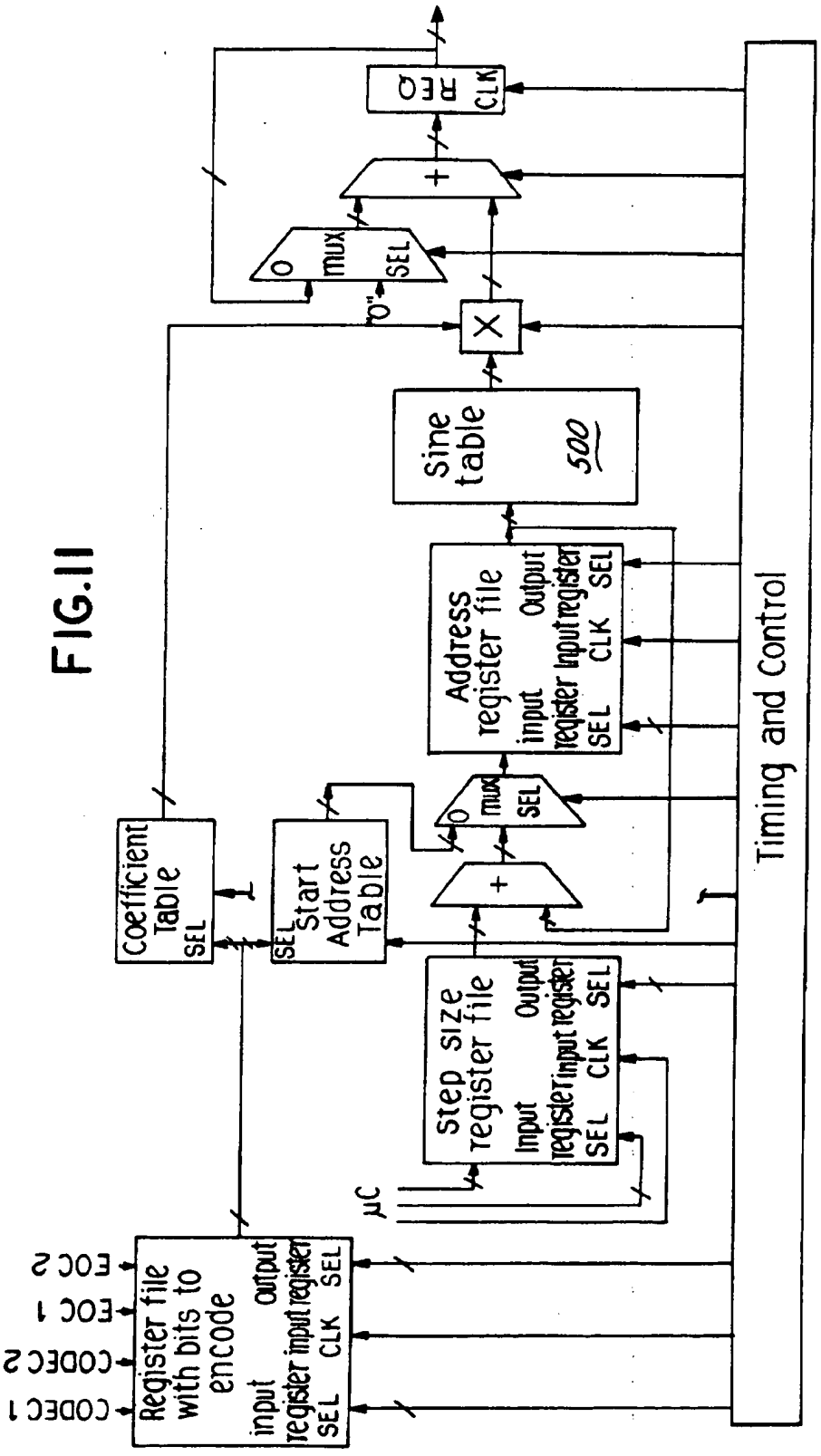

Register file with bits to encode
input register
output register
SEL
CLK
CODEC 1
CODEC 2
EOC 1
EOC 2
μC
Step size register file
Start Address Table
Coefficient Table
Address register file
Sine table
500
mux
SEL
"0"
X
+
Timing and Control

FIG.12

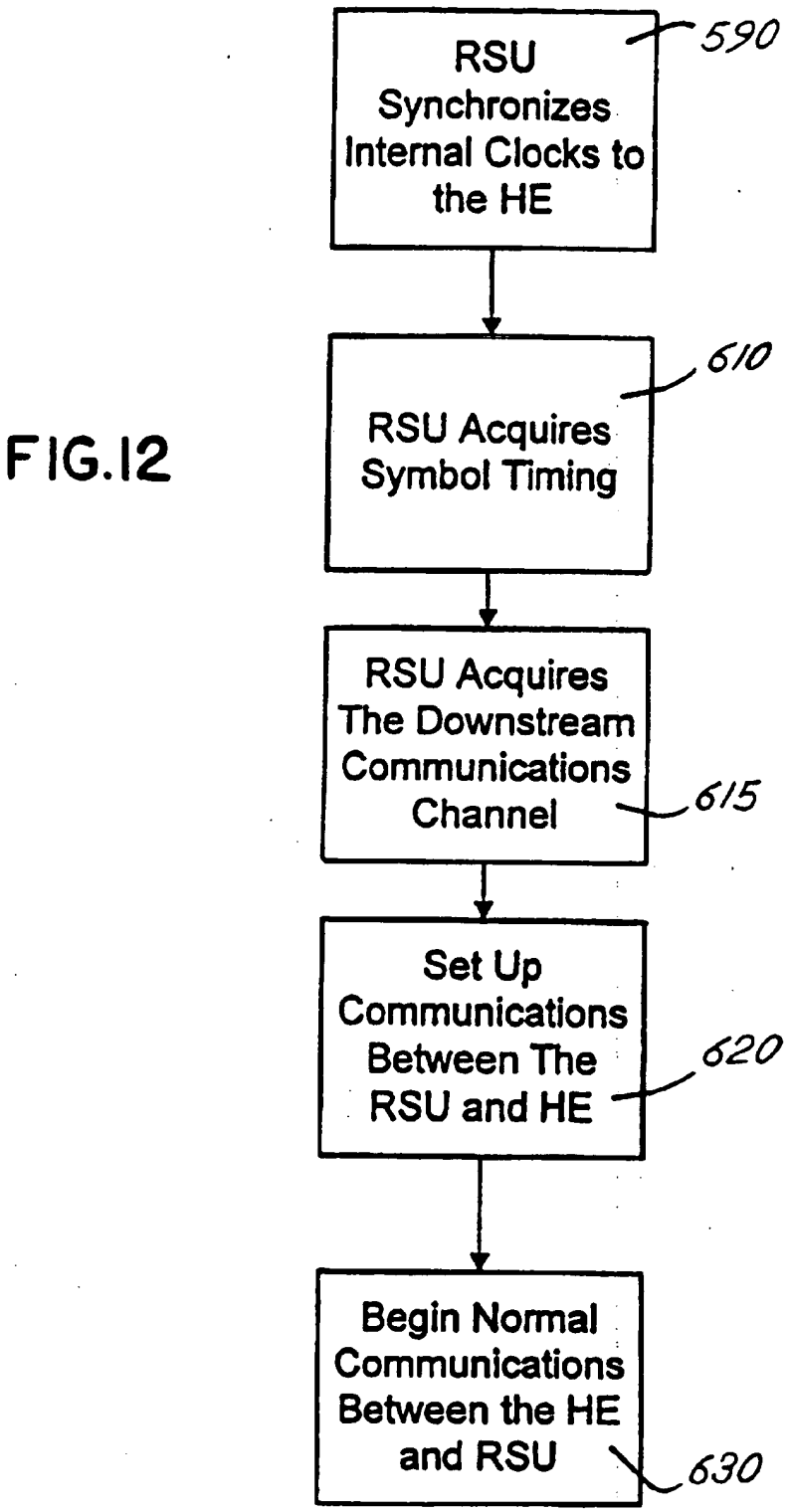

RSU Synchronizes Internal Clocks to the HE
590
RSU Acquires Symbol Timing
610
RSU Acquires The Downstream Communications Channel
615
Set Up Communications Between The RSU and HE
620
Begin Normal Communications Between the HE and RSU
630

FIG.13

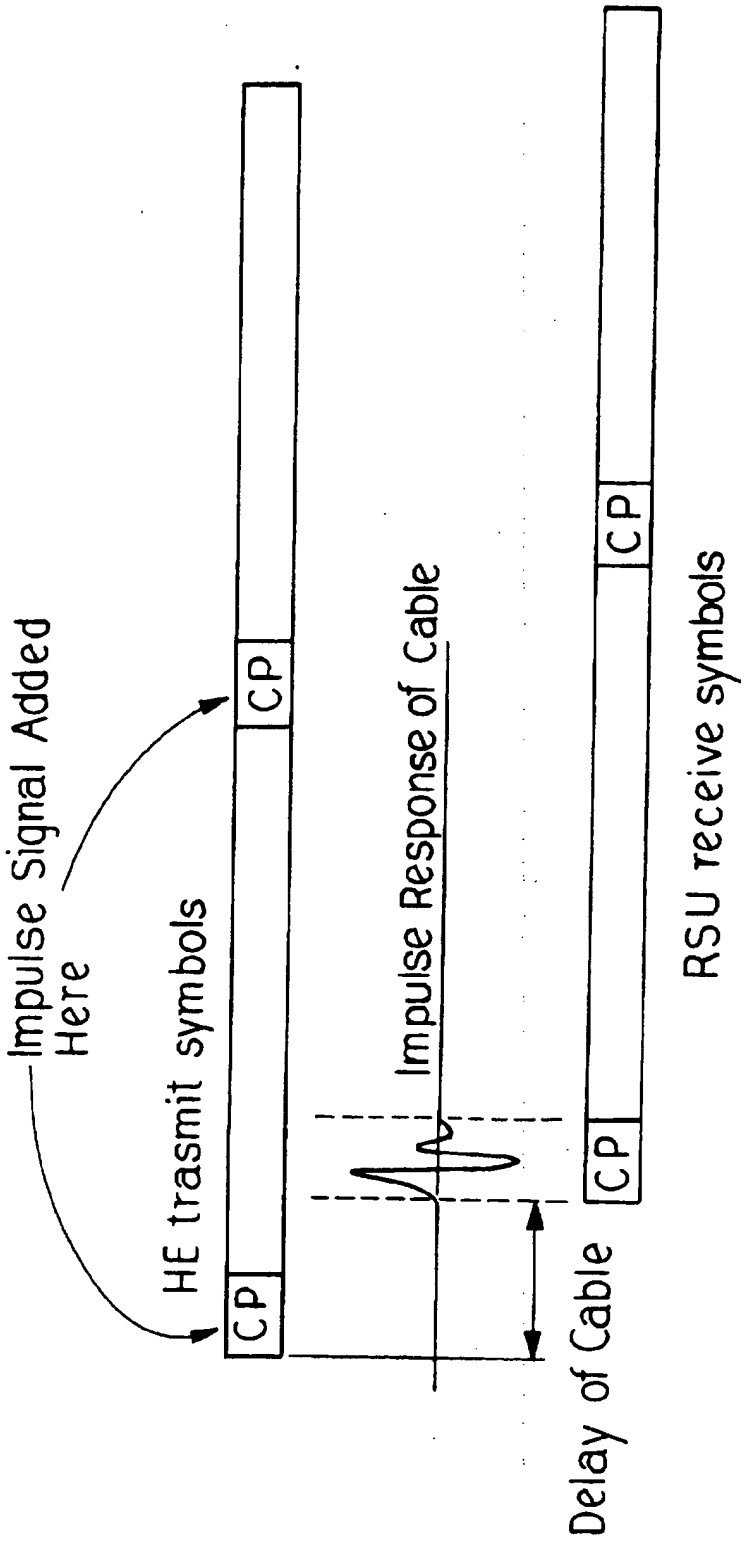
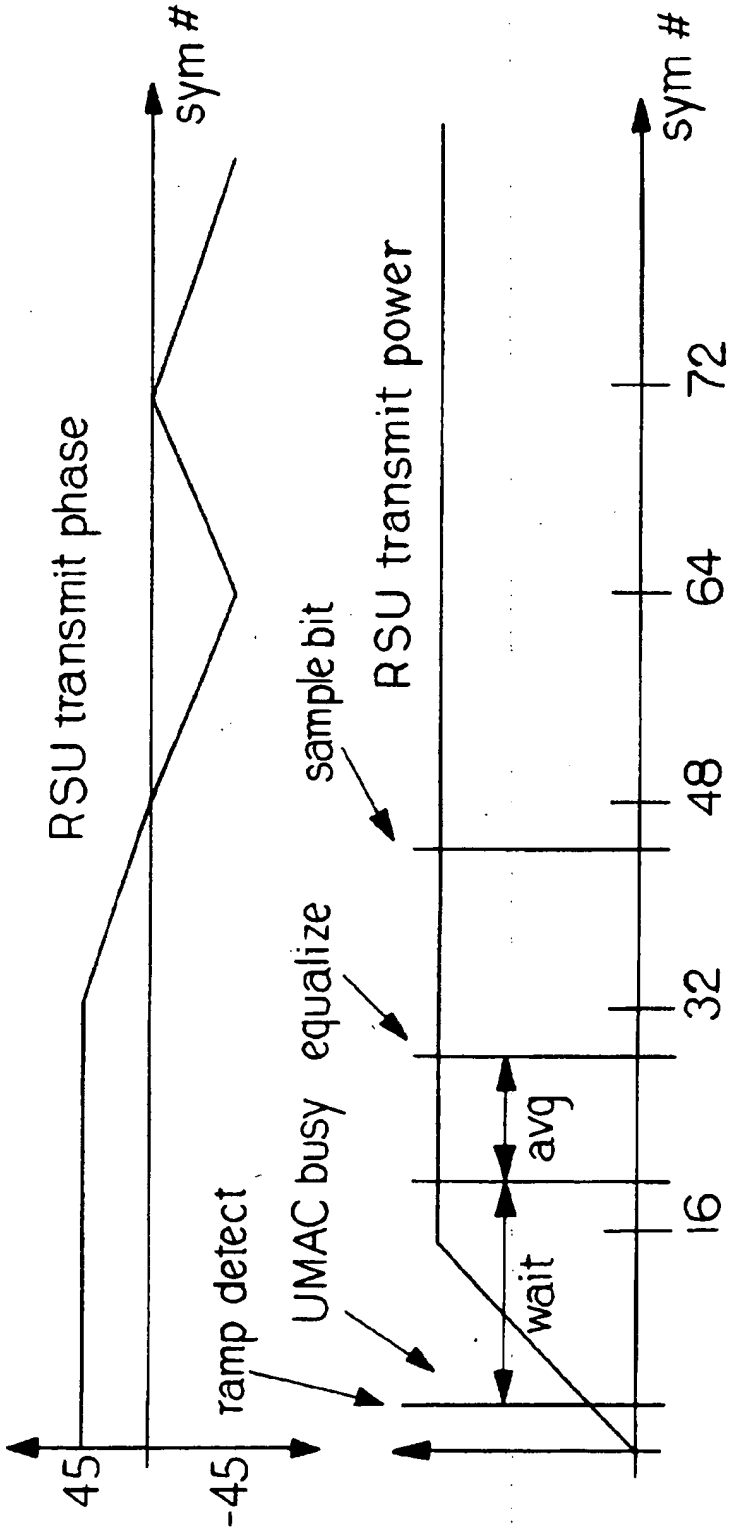

Impulse Signal Added Here
HE trasmit symbols
CP
CP
Impulse Response of Cable
CP
CP
RSU receive symbols
Delay of Cable

FIG. 14


sym #
RSU transmit phase
45
-45
ramp detect
UMAC busy
equalize
sample bit
RSU transmit power
sym #
16
32
48
64
72
avg
wait

MULTI-POINT OFDM/DMT DIGITAL COMMUNICATIONS SYSTEM INCLUDING REMOTE SERVICE UNIT WITH IMPROVED RECEIVER ARCHITECTURE

TECHNICAL FIELD

The present invention is directed to a remote service unit for use in an OFDM/DMT digital communications system. More particularly, the present invention is directed to an improved receiver architecture for use in a remote service unit of a multipoint. OFDM/DMT digital communications system.

BACKGROUND

Multi-point communications systems having a primary site that is coupled for communication with a plurality of secondary sites are known. One such communications system type is a cable telephony system. Cable telephony systems transmit and receive telephone call communications over the same cable transmission media as used to receive cable television signals and other cable services.

One cable telephony system currently deployed and in commercial use is the Cablespan 2300 system available from Tellabs, Inc. The Cablespan 2300 system uses a head end unit that includes a primary transmitter and primary receiver disposed at a primary site. The head end unit transmits and receives telephony data to and from a plurality of remote service units that are located at respective secondary sites. This communication scheme uses TDM QPSK modulation for the data communications and can accommodate approximately thirty phone calls within the 1.9 MHz bandwidth typically allocated for such communications.

As the number of cable telephony subscribers increases over time, the increased use will strain the limited bandwidth allocated to the cable telephony system. Generally stated, there are two potential solutions to this bandwidth allocation problem that may be used separately or in conjunction with one another. First, the bandwidth allocated to cable telephony communications may be increased. Second, the available bandwidth may be used more efficiently. It is often impractical to increase the bandwidth allocated to the cable telephony system given the competition between services for the total bandwidth assigned to the cable service provider. Therefore, it is preferable to use the allocated bandwidth in a more efficient manner. One way in which the allocated bandwidth may be used more efficiently is to use a modulation scheme that is capable of transmitting more information within a given bandwidth than the TDM QPSK modulation scheme presently employed.

The present inventors have recognized that OFDM/DMT modulation schemes may provide such an increase in transmitted information for a given bandwidth. U.S. Pat. No. 5,539,777, issued Jul. 23, 1996, purports to disclose a DMT modulation scheme for use in a communications system. The system principally focuses on applications in which a single secondary site includes a plurality of differing receiver and transmitter devices. The transmitters and receivers used at the secondary site of the system described therein, however, are quite complex and require a substantial amount of processing power. As such, the system disclosed in the '777 patent does not readily or economically lend itself to multi-point communications systems in which there are a large number of secondary sites each having at least one receiver.

SUMMARY OF THE INVENTION

A multi-point communications system is set forth that is particularly useful in communications applications in which

there are a number of remote secondary sites each requiring at least one receiver. The communications system comprises a primary transmitter disposed at a primary site and a plurality of receivers respectively disposed at a plurality of secondary sites. The primary transmitter generates OFDM/DMT transmissions over a first number of transmission bins to transmit communication data in those bins. A transmission medium is used for transmitting the OFDM/DMT transmissions from the primary transmitter at the primary site to the plurality of receivers disposed at a plurality of secondary sites. Each of the plurality of receivers employs a unique receiver architecture that digitally processes exclusively a reduced subset of the first number of bins transmitted by the primary transmitter to recover communication data that is transmitted in the reduced subset of the first number of bins. Such a receiver architecture eliminates much of the complexity typically associated with receiving and processing a wide-band OFDM/DMT signal, thereby making the communications system subject to economical and practical implementation in applications having receivers respectively located at a large number of secondary sites.

Each of the plurality of receivers may comprise a first circuit for converting the analog OFDM/DMT transmissions received from the transmitter of the primary site into digital data and a second circuit for processing the digital data output of the first circuit to extract frequency, amplitude, and phase information from the digital data. A third circuit is provided for limiting the digital data processed by the second circuit to a second number of transmission bins, the second number of transmission bins being a reduced subset of the first number of transmission bins transmitted by the transmitter of the primary site.

The third circuit referenced above may be constructed in several ways. For example, the third circuit may comprise an analog-to-digital converter disposed in the first circuit for converting the analog OFDM/DMT transmissions to the digital data at a sampling frequency which results in aliasing of the digital data characteristics to thereby reduce the number of digital data samples processed by the second circuit. As a further example, the third circuit may comprise a band pass filter disposed in the first circuit for limiting the number of bins that are converted to generate the digital data to a subset of the first number of bins of the OFDM/DMT transmissions. Without limitation, one or both of these data reduction techniques can be employed within a single receiver.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic block diagram of a multi-point communications system having a plurality of remote service units disposed at a plurality of secondary sites wherein each of the remote service units comprises a receiver having an improved receiver architecture.

FIG. 2 is a block diagram of illustrative embodiments of the head end unit and a remote service unit of the communications system of FIG. 1.

FIG. 3 illustrates two symbol constellations that are transmitted in two separate frequency bins in accordance with OFDM/DMT data modulation techniques.

FIGS. 4 and 5 illustrate exemplary bandwidth allocations for the local cable system and the cable telephony system, respectively.

FIGS. 6–8 illustrate various embodiments of the receiver of the remote service unit at various levels of detail.

FIGS. 9–11 illustrate various embodiments of the transmitter of the remote service unit at various levels of detail.

FIGS. 12–14 illustrate one way in which the head end unit and a newly added remote service unit can initialize communications.

DETAILED DESCRIPTION OF THE PREFERED EMBODIMENT

FIG. 1 is a block diagram of a multi-point communications system which may use a remote service unit having the improved receiver and transmitter architectures disclosed herein. As illustrated, the communications system, shown generally at 20 includes a head end unit (HE) 25 disposed at a primary site. The head end unit communicates with a plurality of remote service units (RSUs) 30 respectively disposed at a plurality of secondary sites, over a transmission medium 35 such as a coaxial cable.

The digital communications system 20 may, for example, be a cable telephony system. In such an application, the head end unit 25 is disposed at a cable television transmission facility while the remote service units 30 are disposed at individual customer locations, such as individual customer homes. The transmission medium 35 would be the new or existing transmission cable used to transmit the cable television services. The head end unit 25 in a cable telephony network is responsible for communicating with and interconnecting telephone calls between the plurality of remote service units 30 as well communicating with a central switching office 40 for sending and receiving telephone calls from sites exterior to the local cable television service area.

A block diagram of one embodiment of a head end unit 25 and a remote service unit 30 is shown in FIG. 2. As illustrated, the head end unit 25 and the remote service units 30 each generally comprise respective baseband sections 45, 50 and respective RF sections 55, 60. The baseband section 45 of the head end unit 25 receives constellation data at one or more lines 65 and performs an Inverse Fast Fourier Transform on the received data. The transformed signal is modulated within the RF section 55 for transmission along the cable transmission 35. The remote service units 30 receive the RF modulated data from the cable transmission medium 35 in the respective RF section. The received signal is demodulated within the RF section 60 of the remote service unit 30 and the resulting signal is supplied to the baseband section 50 which performs a Fourier Transform on the signal to recover the data transmitted by the head end unit 25. The recovered data is supplied from the baseband section 50 along one or more lines 70 for further decoding. As is apparent from the block diagram of FIG. 2, constellation data may also be received at one or more lines 75 of the baseband section 50 of the remote receiving unit 30. The received data undergoes an Inverse Fourier Transformation or, more preferably, a direct sequence transformation and the resulting signal is RF modulated for transmission along the cable transmission medium 35 for receipt by the head end unit 25. The head end unit 25 demodulates the received signal in the RF section 55 and performs a Fast Fourier Transform on the demodulated signal to recover the transmitted data and provide it on one or more lines 80 for further decoding.

The present system 20 utilizes OFDM/DMT digital data modulation for exchanging communications data between the head end unit 25 and the remote service units 30. Such OFDM/DMT digital data communications assign a particular amplitude, frequency, and phase for each transmitted "sub-symbol". The transmitted "sub-symbol" represents one or more information data bits that are to be transmitted between the units 25 and 30. Each sub-symbol may be represented by a point within a "constellation", the point being transmitted at a given carrier frequency or "bin". FIG. 3 illustrates the use of two constellations 90 and 95, each having sixteen constellation points that are capable of being transmitted within two separate frequency bins. As illustrated, a sub-symbol having a carrier signal of frequency f1 has its amplitude and phase varied depending on the constellation point that is to be transmitted. For example, a constellation point representing the binary states 0000 is transmitted as a sub-symbol at a phase of θ_2 and an amplitude of A_1 during a designated symbol time. A constellation point representing the binary states 1111, however, is transmitted as a sub-symbol at a phase of θ_2 and an amplitude of A_2 during a designated symbol time. Similarly, the second constellation 95, preferably having the same amplitude and phase designations for its sub-symbols as the first constellation 90, is used to modulate a second carrier frequency f2. The resulting modulated signals are combined into a single output symbol in which the individual sub-symbols are differentiated from one another based on their respective carrier frequencies or "bins". It will be recognized that many variations of the disclosed OFDM/DMT transmission scheme are possible, the foregoing scheme being merely illustrated herein to provide a basic understanding of OFDM/DMT communications.

Referring to FIG. 4 there is shown an exemplary break-up of the bandwidth allocated to a local cable television service. As illustrated, the entire allocated bandwidth is further sub-allocated into smaller bandwidth portions for the transmission of selected services such as cable television, audio broadcasting, cable telephony, and other miscellaneous services. The bandwidth allocated for cable telephony constitutes the focus of further discussion. However, it will be recognized that the digital communications system described herein can be utilized in any multi-point digital data communications system.

FIG. 5 illustrates the bandwidth allocated, for example, to the cable telephony communications. Without limitation, the bandwidth of the exemplary embodiment may be about 2 MHz with a center frequency of about 600 MHz. As shown, the bandwidth is divided into a plurality of frequency bins 100, each bin carrying a sequence of subsymbols corresponding to the data that is to be communicated. The head end unit 35 sends and receives data to and from multiple remote service units 30 and must be capable of processing substantially all, if not all of the bins allocated to cable telephony transmission. Accordingly, the head end unit 25 must have a substantial amount of processing power. Such a high amount of processing power naturally gives rise to increased production, maintenance, and power costs. Similarly, the remote service units 30 require substantial processing power if they are to each process the entire bandwidth or number of bins allocated to the cable telephony communications and transmitted by the head end unit 25.

The present inventors, however, have recognized that many applications using multi-point, OFDM/DMT data communications do not require that the remote service units 30 process the entire number of bins transmitted by the transmitter at the primary site. Rather, as recognized by the present inventors, the remote service units 30 employed in many types of OFDM/DMT data communications systems, such as cable telephony systems, need only be capable of processing a limited number of bins of the entire number of bins transmitted by the head end unit 25.

Based on this recognition, the remote service units 30 are designed to process substantially fewer bins than the entire

number of bins transmitted by the head end unit **25**. More particularly, the receiver architecture of each RSU is particularly adapted to exclusively digitally process only a limited number of bins of the larger number of OFDM/DMT bins that are transmitted by the head end unit **25**. Remote service units **30** disposed at different secondary sites are preferably designed to process different subsets of bins. More preferably, the particular subsets of bins processed by any remote service units is dependent on command transmissions received from the head end unit **25**.

Such a receiver architecture has several advantages. For example, the digital signal processing capability required by the receiver of each RSU is significantly reduced thereby making each RSU more economical to design, manufacture, and maintain. Additionally, each RSU consumes less power than would otherwise be required if each RSU had to process the complete number of bins sent by the head end unit **25**.

FIG. **6** is a schematic block diagram of one embodiment of a receiver **110** suitable for use in the remote service units **30**. As illustrated, the exemplary embodiment is comprised of five functional sections: an RF conversion section **115**, an IF-to-digital conversion section **120**, a Fourier Transform section **125**, a decoding and framing section **130**, and a timing and control logic section **140**.

The RF conversion section **115** receives the RF signal from the transmission medium **35** through, for example, a splitter, and transposes the desired part of the OFDM/DMT spectrum containing the information that is to be recovered into a predetermined intermediate frequency (IF) pass band. As will be readily recognized, and as will be set forth in further detail below, the RF conversion is achieved with a combination of mixers, filters, and frequency synthesizers.

The IF-to-digital section **120** is used to sample the IF analog signal output of the RF conversion section **115** and provide a digital output signal corresponding to fewer than all of the bins transmitted by the head end unit **25**. The resulting digital output signal can thus be processed by the Fourier Transform section **125** using substantially less processing power than would otherwise be required to process the full number of bins. The desired output signal is achieved by band pass filtering the signal to provide a signal that comprises a subset of the original OFDM/DMT bins transmitted by the head end unit **25**. This filtered signal is then under-sampled such that the desired signal folds down to near base band via an aliasing process. Under-sampling permits the use of a lower frequency A-to-D conversion than would otherwise be required. Additionally, the under sampling reduces the number of digital samples that are generated, thereby reducing the amount of processing power required in subsequent digital processing steps in the Fourier Transform section **125**.

It will be recognized, however, that under sampling is not the only choice for reducing the number of digital samples that are generated to the subsequent sections. For example, a mixer could be used to mix the filtered signal to base band thereby reducing the sampling frequency required to properly sample the received signal. This too would allow one to take advantage of the reduced bin receiver to reduce speed, complexity, and power usage of the system.

The Fourier Transform section **125** is used to take the Fourier transform of the sampled signal output from the IF-to-digital section **120** in order to obtain a frequency domain representation of the OFDM/DMT modulated signal. This can be achieved in any one of multiple ways. First, the Fourier Transform section **125** may include a digital signal processor that performs a Fourier Transform on the sampled data. However, unlike ordinary OFDM/DMT digital communications which perform a Fast Fourier Transform over all the bins sent by the transmitter at the primary site, the Fourier Transform implemented by the presently disclosed receiver **110** is taken over a reduced number of bins. This results in significant cost and power savings. A further improvement can be achieved in the case where the sampled signal received from the IF-to-digital section **120** contains more bins than any individual receiver needs to receive. In this case, a hardware correlator could be used to obtain a Fourier Transform of only the bin frequencies containing data that the receiver **110** is to recover. This permits further power and complexity reduction when the narrow band receive window is still somewhat larger than the needed bandwidth. Furthermore, this architecture allows the speed and power consumption to be scaled according to the number of bins any particular receiver needs to receive.

It will be recognized that an FFT can be performed on the reduce subset of received bins yet still reap the advantages inherent in the disclosed receiver architecture. This is due to the fact that the FFT can be implemented using a digital signal processor of reduced complexity when compared to an FFT processing the entire bandwidth transmitted by the head end unit **25**.

The decoding and formatting section **130** receives the processed output of the Fourier Transform section **125** and converts the received frequency domain constellation points into the corresponding data they represent thereby completing the recovery of the transmitted data. The decoding and formatting section **130** also performs any error correction, digital equalization, slicing to bits, framing, and descrambling that is required. Such decoding and formatting, as is readily recognized, is dependent on the framing and formatting used by the head end unit **25** in transmitting the data and may take on any form.

It is worth noting that phase compensation can be implemented in the decoding and formatting section **130** to compensate for any differences between the mixing frequencies of the transmitter of the head end unit **25** and the mixing frequencies of the receiver of the remote service unit **30**. Such phase compensation can be implemented by effectively rotating the phase of each received sub-symbol through a predetermined phase angle θ_3 during each symbol period. As such, the phase angle through which each sub-symbol is rotated is a multiple of θ_3. For example, a first sub-symbol during a first symbol period T1 is rotated by phase angle θ_3 while the next sub-symbol received during a subsequent second symbol period T2 is rotated by a phase angle equal to $2^* \theta_3$.

The output from the decoding and formatting section **130** is supplied to the input of one or both of an analog-to-digital section **132** and direct digital section **137**. The analog-to-digital section **132** converts the digital information received from the decoding and formatting section **130** to an analog signal that may be supplied to various analog devices. The direct digital section **137** provides an interface between the digital signal output of the decoding and formatting section **130** and any digital data devices.

A centralized timing and control block **140** is used in the illustrated embodiment to provide the timing and control signals required to coordinate the operation of the other processing sections. It will be recognized, however, that this timing and control function may also be performed in a decentralized way, wherein each of the individual processing sections **115**, **120**,**125**, and **130** contain or share individual timing and control circuitry. However, in such

instances, additional synchronization circuitry dealing with the resulting asynchronous nature of the clocks in the individual sections may be required. Such a decentralized architecture could also require more pipelining with its associated memory.

FIG. 7 illustrates one manner in which the RF section 115, the IF-to-digital section 120, and a portion of the Fourier Transform section 125 can be implemented. As shown, the signal transmitted from the head end unit 25 is received by a first bandpass filter 150 that, for example, has a wide pass band with end frequencies of about 470 MHz and 750 MHz. The signal from the bandpass filter 150 is supplied to the input of a tuner 155 that has its characteristics determined by the output of a tuner synthesizer 160 that is tied to receive the output of a reference clock that, for example, has a clock frequency of about 4 MHz. Without limitation, the tuner 155 mixes the signal from the bandpass filter 150 to a signal having a frequency of about 240 MHz. The output of the tuner 155 is supplied to the input of a further filter 165, a SAW filter in the illustrated embodiment. The output of SAW filter 165 is supplied to an IF mixer 170 that transposes the signal to an intermediate frequency (IF) of, for example, 10.7 MHz. The mixer 170 performs the IF conversion by mixing the signal received from the SAW filter 165 with the signal generated by oscillator 175. The signal generated by the oscillator 175 is synchronized to the reference clock signal received on line 180.

The received signal, now converted to the IF band, is subsequently supplied to the input of an IF bandpass filter 185 that, for example, has a 300 KHz bandwidth and a center frequency of about 10.7 MHz. The output of the bandpass filter 185 is an OFDM/DMT modulated signal having only a subset of the entire number of bins transmitted by the head end unit 25. One or both of the filters 165 and 185, however, may be used to reduce the bandwidth of the received signal so as to limit the number of bins that are ultimately processed. The filtered IF signal is converted to a digital signal by an A/D converter 190 that has its conversion clock on line 195 synchronized to the reference clock on line 180 through a clock dividing circuit 200. As noted above, the conversion clock frequency may be selected to be low enough to result in undersampling of the IF signal thereby reducing the number of samples supplied at the A/D converter 190 output. An increased in the sampling rate, however, can be used to compensate for any inexactness of filters 170 and/or 185.

The output of the A/D converter 190 is supplied to the input of a digital signal processing circuit 205 that generates the Fourier Transform of the signal that it receives, extracts the received symbols based on the Fourier Transform information, and performs any other processing functions required. In a cable telephony system, the output of the digital processing circuit 205 may be supplied to the inputs of one or more D/A converters or CODECs that convert the data contained in the received symbols to one or more analog output signals, such as audio voice signals, that can be heard by a person engaged in a telephone conversation.

FIG. 8 illustrates one embodiment of a hardware correlator 210 that may be used in the Fourier Transform section 125. The illustrated hardware correlator 210 is designed to correlate nine frequency bins within the total bandwidth of frequency bins that are provided in digital format at the output of the A/D converter 190 of, for example, the IF-to-digital circuit 120. The correlator 210 includes a multiplier section 215, a frequency generator section 220, and an accumulator section 225. As shown, the multiplier section 215 receives the digital data that is output from the IF-to-digital section 125 and multiplies each value by the sine and cosine value of each of the nine frequency bins. The sine and cosine values are supplied as inputs to the multiplier 215 from the frequency generator section 220. The frequency generator section 220 includes a step-size register 225 that includes, in the present embodiment, nine register locations that are programmed by a microcontroller or digital signal processor. The values stored in the step-size register 225 are used to determined the step-size of the addresses supplied to address the data in a cosine table ROM 230, shown here has a quarter wave cosine table. An address modifier circuit 235 receives the address data from the address register 240 and modifies the data so that the address data supplied to the cosine table ROM 230 falls within an acceptable range of addresses and thereby accesses the proper portion of the wave. A sine/cosine bit is supplied from, for example, the timing and control circuit 140 so that each value received from the IF-to-digital converter 125 is multiplied by both the sine and cosine values of each of the nine frequency bins. The data resulting from the multiplication operation are accumulated in the accumulator section 225 and output to the decoder/ formatting section 130 for further processing.

One embodiment of a transmitter suitable for use in the remote service units 30 is illustrated in FIG. 9. The transmitter, shown generally at 300 transmits its digital data in an OFDM/DMT modulated format using a number of bins that is less than the number of bins transmitted and received by the head end unit 25. Accordingly, the transmitter 300 can generate the OFDM/DMT transmission output by modulated direct digital synthesis.

The transmitter 300 of the illustrated embodiment is designed to accept both analog and digital signal information for OFDM/DMT transmission. Accordingly, the transmitter 300 includes an analog-to-digital interface unit 305 and a direct digital interface unit 310. The analog-to-digital interface unit 305 is used to sample an analog signal, such as a voice signal of a person engaged in a telephone conversation, and convert it to digital data to be transmitted. For example, the analog-to-digital interface unit 305 may contain CODECs and SLICs for connecting one or more telephones to the system.

The direct digital interface unit 310 interfaces with any type of device that provides a signal that is already in digital format. For example, the direct digital interface unit 310 might have a serial interface for receiving data, as in a modem application. The unit 310 might also receive data from a system CPU to be sent to the receiver of the head end unit 25.

The transmitter 300 also includes a data interface unit 315. The data interface unit 315 receives data from any combination of the following: sampled analog data from the output of the analog-digital interface unit 305, direct digital data from the output of the direct digital interface unit 310, or other digital data sources that, for example, provide system communication information generated from within or without the data interface unit 315. The data interface unit 315 formats the data received from these data sources into a single data stream. Tasks such as data framing, scrambling, error correction coding, CRC generation, data synchronization, and stuffing may be performed by the data interface unit 315 as part of the formatting function. Optionally, the data interface unit 315 may group the data into words that represent the unique constellation points to be transmitted. As will be readily recognized, the specific formatting operations executed by the data interface unit 315 are dependent on the particular requirements of the communications system in which the remote service unit 30 is employed.

The serial data stream output from the data interface unit **315** is supplied to the input of the transmit engine circuit **320**. The data that the transmit engine circuit **320** receives includes one constellation point for each OFDM/DMT bin of the reduced set of bins that is active during a single symbol time. The transmit engine circuit **320** is responsible for calculating the Inverse Fourier Transform on the data stream that is to be modulated and for producing a time domain sequence for each symbol along with any cyclic prefix. Generally, systems using OFDM/DMT modulation performs this function using an IFFT that is implemented, for example, with a digital signal processor. However in a multi-point application, such as the communication system disclosed herein, only a limited number of the possible frequencies or bins are used by each secondary transmitter. Given that only a portion of the total available transmission bandwidth is utilized, the disclosed secondary transmitter architecture is more efficient and cost-effective.

In the preferred embodiment of the transmit engine circuit **320**, the time domain sequence is generated by modulated direct digital synthesis, sample by sample. In addition to reducing the complexity of the transmitter, this operation reduces system latency. The time domain sequence for a given symbol is created by generating sine waves, sample by sample, and adding them together. The frequency determines the bin in which the data will be received. The phase and amplitude are used to convey the data intelligence.

Additionally, the preferred embodiment of the system is such that there are **256** bins between 0 Hz and the Nyquist frequency. This is typical in OFDM/DMT systems. That is, the spectrum between 0 Hz and the Nyquist frequency is divided into a number of bins wherein the number is a power of 2, i.e. 2^n where n is an integer. This facilitates the use of FFTs and IFFTs . However, the presently disclosed transmitter **300** preferably uses a Nyquist frequency that is greater than the transmit bandwidth, thereby leaving a number of bins turned off on each edge. Such a transmission scheme provides a natural filtering effect at the edges of the bandwidth. In the preferred embodiment, 209 bins fit within the allocated transmit bandwidth. An additional eight bins are turned off on either end of that bandwidth to leave some transition bandwidth for filters.

Optionally, the transmitter **300** may utilize a digital filter **325** that receives the output of the transmit engine circuit **320**. This optional filter performs any desired digital filtering of the output stream and, for example, may be useful in further limiting the bandwidth of the signal.

The digital sequence output from either the digital filter **325** or the transmit engine circuit **320** is supplied to the input of a digital-to-baseband converter or a digital-to-IF converter **330** depending on whether the signal output is at an IF or at baseband. The converter **330** includes components that perform digital-to-analog conversion and analog filtering. If the output is at an IF, a bandpass filter centered around any image of the output spectrum may be employed. This results in an IF signal that is more easily processed in subsequent operations.

The output of the converter **330** is supplied to the input of an RF frequency converter **335**. The RF frequency converter **335** shifts the OFDM/DMT spectrum from IF or baseband to the desired RF frequency. As will be readily recognized, the RF frequency converter **335** may be implemented using a combination of mixers, filters, and frequency synthesizers to implement the conversion functions and provides an OFDM/DMT output that is suitable for transmission along the transmission medium.

Timing and control of the transmitter system **300** is provided by a common timing and control logic circuit **340**. A centralized timing and control circuit **340** is used in the illustrated embodiment. This function, however, could also be performed in a decentralized way. If decentralized timing and control are utilized, the timing and control circuits would likely be more complex to deal with the resulting lack of synchronism between circuits. It could also require more pipelining with its associated memory.

One embodiment of digital transmission circuitry that may be used to generate the digital OFDM/DMT signal for subsequent D/A conversion and RF modulation is set forth in FIG. **10**. The digital transmission circuitry **350** illustrated here may be used to implement, inter alia, the transmit engine circuit **320** of FIG. **9**. The digital transmission circuitry **350** accepts digital data from, for example, the output of first and second CODECs respectively associated with individual first and second telephones. Additionally, the circuitry **350** may receive digital data that is to be transmitted in embedded control channels within the transmitted signal, each of the embedded control channels being respectively associated with one of the first and second telephones. The digital data output from the CODECs and on the embedded control channels are combined together by a combiner circuit **360** into two separate data groups, illustrated here as DATA1 and DATA2. The presently disclosed embodiment provides the capability of generating OFDM/DMT transmissions in one or more of nine frequency bins.

Each data group DATAL and DATA2 is supplied to the input of an encoder logic circuit **365**. The encoder logic circuit **365** divides the data groups into symbol groups and maps each symbol to a point of a constellation to obtain a phase and amplitude for each symbol. The amplitude information for each symbol is provided on one or more lines **370**, while the phase information for each symbol is provided on one or more lines **375**.

Generation of the desired frequency and phase for each symbol takes place through the interrelated operation of the start address selection ROM **380**, the step size selection register **385**, adder **390**, address register **395**, address modifier **400**, and sine table ROM **405**. The sine table ROM **405** contains the digital data representation of a sine wave, or selected portion thereof, shown here as a quarter wave table, in successive addressable memory locations. The successive, addressable memory locations of the sine table ROM **405** are addressed in a specific manner to provide a digital output signal having the phase and frequency characteristics of the symbol that it is to represent. The phase of the sine wave represented by the digital output signal is dependent on the memory location that is first addressed at the beginning of the symbol period while the frequency of the sine wave is determined by the rate at which successive memory locations within the sine table ROM **405** are addressed.

The selection of the memory location that is first addressed at the beginning of a symbol period is dependent on the phase information on output lines **375** of the encoder logic circuit **365**. The phase information is supplied to the start address ROM **380** which provides a start address which is output to the address storage register **395**. The step size through which the memory locations within the sine table ROM **405** are to be cycled is determined by the value at the output of the step size storage register **385**.

The step size storage register **385** includes one or more memory storage locations that are accessible to a microcontroller or DSP. The microcontroller determines the step sizes

that are stored in the step size storage register **385** based on the desired symbol carrier frequency bins that can be used—the larger the step size, the higher the carrier frequency. In the illustrated embodiment, the step size register **385** includes nine register locations for the nine bins that can be transmitted. Preferably, the step size register **385** is programmed by the microcontroller based on commands received from the head end unit **25**. The step size value is supplied at one or more output lines **410** of the step size register **385** to the input of the adder **390**. The adder **390** functions to provide the address signals that are used to successively address the memory locations of the sine table ROM **405**. Accordingly, the output of the address register **395** is fed back to the input of the adder **390** so that the sine table ROM **405** selection address is incremented by the appropriate step size on each successive addressing cycle corresponding to the particular frequency bins.

Since the sine table ROM **405** of the present embodiment only contains a portion of a single sine wave, an address modifier **400** is used. The address modifier **400** includes combinatorial and/or programmed logic circuits that perform calculations that ensure that the address value supplied to the sine table ROM **405** falls within an acceptable range and thereby accesses the appropriate portion of the wave. Such calculations ensure that the newly calculated address starts at the appropriate portion of the sine table ROM **405** without generating an undesired discontinuity.

The output of the sine table ROM **405** is supplied to the input of a multiplier **420**. The multiplier **420** accepts each digital data value that is output from the sine table ROM **405** and multiplies each value by the corresponding amplitude factor as determined from the amplitude information output of the encoder logic circuit **365** received along lines **370**.

Since the sine table ROM **405** of the presently disclosed embodiment includes only positive values, some circuitry must be provided to generate the negative portions of the wave. To this end, the output of the multiplier **420** is supplied to a two's complement converter **430** and the most significant bit (MSB) from the address register **395** is used to signal the converter **430** to either through-connect the output of the multiplier **420** to an accumulator **440** or perform a two's complement operation on the output before providing it to the accumulator **440**. The accumulator **440** adds all of the data points for the nine frequency bins that are generated during a single sample period and provides the resulting data on output lines **445**.

As will be readily recognized, the timing and control inputs from the timing and control logic circuitry **340** are not illustrated in FIG. **10**. Such inputs have been omitted in order to simplify the figure. Given the foregoing description, the timing and control operations can be readily derived.

FIG. **11** shows yet a further embodiment of the basic elements of the transmit engine shown in FIG. **10**. In the embodiment of FIG. **11**, a full wave sine table ROM **500** is utilized. Accordingly, the two's complement circuit **430** and the address modifier **400** are not provided.

Although not particularly pertinent to the improved receiver architecture disclosed herein, FIGS. **12–14** illustrate one manner of initiating communications between a newly added or powered-up remote service unit **30** and the head end unit **25**. As shown at step **590**, the remote service unit **30** first synchronizes its internal clocks with the head end unit **25**. One way in which this may be accomplished can be described with reference to FIG. **2** which shows a pilot tone added by the head end unit **25** to a predetermined bin output that is transmitted to the remote service units **30**. The pilot tone is extracted from the received signal by the receiver of the remote service unit **30** and used, for example, as a reference signal for a phase-locked-loop circuit **600**. The output of the phase-locked-loop **600** is provided to the input of a voltage controlled oscillator **605** which generates the reference clock for the remote service unit **30**.

After the clock synchronization of step **590** is completed, the remote service unit **30** acquires its symbol timing at step **610**. One way in which symbol timing may be acquired is illustrated in FIG. **13** which shows an impulse signal **615** being added by the head end unit **25** to the cyclic prefix CP of each symbol transmission. Preferably, the impulse signal **615** reverses polarity with each successive symbol transmission so that a positive polarity impulse signal is added to the cyclic prefix of one symbol transmission while a negative polarity impulse signal is added to the cyclic prefix of the subsequent symbol transmission.

The receiver **110** of the remote service unit **30** finds the time location of the transmitted impulse signal by sampling, at a predetermined rate, the symbols that it receives and alternately adding and subtracting the samples of individual sample periods over several symbol periods. For example, the receiver **110** may sample the received signal at a rate of 100 samples per symbol period to generate samples SA0 . . . SA99 during a first symbol period, SB0. . . SB99 samples that it receives during a subsequent symbol period, SC0 ... SC99 samples that it receives during a subsequent third symbol period, and so on. A first sum Y0 is generated from the first sample period of each sampled symbol period in accordance with Y0=SA0–SB0+SC0 . . . . Similar sums are generated for each of the sample periods through Y99 and the resulting sums are analyzed to determined where the peak amplitude occurs in the sampled symbol period. The time position of the peak amplitude corresponds to the time position of the added impulse signal and, thus, the time position of the cyclic prefix occurring at the beginning of each transmitted symbol. The receiver **110** can then make the requisite adjustments to ensure that it receives the symbols in proper alignment.

Once the receiver **110** has acquired downstream symbol alignment, the system proceeds to step **615** where it acquires the downstream communications channel. The downstream communications channel comprises one or more bins used by the head end unit to establish initial communications with receivers **110**.

After the receiver **110** has acquired the downstream communications channel, setup of the remote service unit communications proceeds to step **620**. At step **620**, the newly added or newly powered-up remote service unit **30** must inform the head end unit **25** that it is in need of registration whereby, among other things, the head end unit **25** allocates bins to the receiver and transmitter of the remote service unit **30**. One problem associated with any initial transmission from the remote service unit **30** to the head end unit **25** is that the transmit boundary of the newly added remote service unit is not aligned with the transmit boundary of the other remote service units on the system. Thus, any misaligned transmission from the newly added remote service unit may corrupt the transmissions received from other remote service units.

One way of overcoming the problem of initial misalignment is illustrated in FIG. **14**. To overcome the problem, a predetermined upstream bin is allocated as an upstream multi-access channel. The transmitter of the newly added remote service unit transmits information on the upstream multi-access channel in the illustrated manner by altering

both its transmit phase and transmit power. As shown, the newly added remote service unit first maintains its transmit phase at a predetermined phase while gradually increasing the transmit power. The head end unit **25** can receive such a signal without a corresponding corruption of the data transmitted from the other remote service units. Once the head end unit **25** detects the transmission from the newly added remote service unit, it can perform any requisite processing of the received signal, such as equalization thereof. After a predetermined period of time has elapsed, the newly added remote service unit begins to slowly vary the phase of its transmitted signal in the illustrated manner. The transmit phase is varied so as to convey intelligent data to the head end unit **25**. Accordingly, the head end unit **25** samples the phase of the signal that it receives on the upstream multi-access channel and uses the data, for example, to identify the newly added remote service unit.

After the newly added remote service unit has been identified by the head end unit **25**, the head end unit **25** commands the newly added remote service unit, via the downstream communications channel, to send, for example, an impulse signal of a predetermined amplitude on the upstream communications channel at the symbol rate. Using the same basic method described above in connection with the remote service unit, the head end unit **25** detects the time position of the impulse signal and provides the remote service unit with the information necessary to align its symbol transmissions with the symbol transmissions of the other remote service units. Further communications between the newly added remote service unit and the head end unit **25** can take place on the upstream and downstream communications channels until the head end unit **25** allocates the transmit and receive bins that are to be assigned to the newly added remote service unit and instructs it accordingly. Once the foregoing has been completed, the head end unit **25** and the newly added remote service unit carry out their standard communications at step **630**.

Of further note, although not of particular importance to the improved receiver architecture, is the fact that the present system can be designed to transmit and receive either 4 point constellations or 16 point constellations in a given bin depending on the signal-to-noise ratio in the communications system at the bin frequency. This determination is made by the head end unit **25** and the remote service unit(s) transmitting and/or receiving in that bin are instructed accordingly. In bins having a low signal-to-noise ratio, it is preferable to use 4 point constellations. In bins having a high signal-to-noise ratio, it is preferable to use 16 point constellations.

With the foregoing in mind, it can be seen why the embodiments of the remote service units described herein send and receive data in nine bins, respectively. In high noise conditions, four bins are needed by each of the two phones at the customer site to transmit data and four bins are needed by each of the two phones at the customer site to receive data. A total of eight bins are thus required in high noise conditions for each telephone receiver and transmitter, respectively. The further ninth bin may, for example, be used to facilitate a bin swapping function.

Although the present invention has been described with reference to specific embodiments, those of skill in the art will recognize that changes may be made thereto without departing from the scope and spirit of the invention as set forth in the appended claims.

We claim:

1. In a multi-point communications system having a receiver and transmitter disposed at a primary site for communication with a plurality of remote service units disposed at respective secondary sites, the transmitter of the primary site using OFDM/DMT transmissions over a first number of transmission bins to transmit communication data, a receiver for use in one or more remote service units comprising:

first means for converting the analog OFDM/DMT transmissions received from the transmitter of the primary site into digital data;

second means for processing the digital data of the first means for extracting frequency, amplitude, and phase information from the digital data;

third means for limiting the digital data processed by the second means to extract the frequency, amplitude, and phase information to a second number of transmission bins, the second number of transmission bins being a reduced subset of the first number of transmission bins transmitted by the transmitter of the primary site, whereby the receiver digitally processes the reduced subset of bins of the received signal to the exclusion of other bins of the first number of transmission bins.

2. A receiver as claimed in claim **1** and further comprising decoding means for receiving the frequency, amplitude, and phase information from the second means and decoding the information to recover the communication data imposed on the OFDM/DMT signal by the transmitter at the primary site.

3. A receiver as claimed in claim **1** wherein the first means comprises:

an RF frequency conversion circuit connected to receive the OFDM/DMT transmissions that are transmitted by the transmitter of the primary site for converting the received OFDM/DMT transmissions to an intermediate frequency;

an IF-to-digital conversion circuit for receiving the OFDM/DMT transmissions at the intermediate frequency and converting the transmissions to the digital data.

4. A receiver as claimed in claim **1** wherein the second means comprises means for executing a Fourier Transform on the digital data.

5. A receiver as claimed in claim **1** wherein the second means comprises a correlator.

6. A receiver as claimed in claim **1** wherein the third means comprises an analog-to-digital converter disposed in the first means for converting the analog OFDM/DMT transmissions to the digital data at a sampling frequency which results in aliasing of the digital data characteristics thereby to reduce the number of digital data samples processed by the second means.

7. A receiver as claimed in claim **1** wherein the third means comprises a band pass filter disposed in the first means for limiting the number of bins that are converted to generate the digital data to a subset of the first number of bins of the OFDM/DMT transmissions.

8. A multi-point communications system comprising:

a primary transmitter disposed at a primary site, the primary transmitter generating OFDMIDMT transmissions over a first number of transmission bins to transmit communication data;

a plurality of receivers respectively disposed at a plurality of secondary sites;

a transmission medium for transmitting the OFDM/DMT transmissions from the primary transmitter at the primary site to the plurality of receivers disposed at a plurality of secondary sites

each of the plurality of receivers digitally processing a reduced subset of the first number of bins transmitted by the primary transmitter to recover communication data that is transmitted in the reduced subset of the first number of bins to the exclusion of digitally processing other views in the first number of bins.

9. A multi-point communications system as claimed in claim 8 wherein each of the plurality of receivers comprises:

first means for converting the analog OFDM/DMT transmissions received from the transmitter of the primary site into digital data;

second means for processing the digital data of the first means for extracting frequency, amplitude, and phase information from the digital data;

third means for limiting the digital data processed by the second means to a second number of transmission bins, the second number of transmission bins being a reduced subset of the first number of transmission bins transmitted by the transmitter of the primary site.

10. A multi-point communications system as claimed in claim 9 wherein the first

means comprises:

an RF frequency conversion circuit connected to receive the OFDM/DMT transmissions that are transmitted by the transmitter of the primary site for converting the received OFDM/DMT transmissions to an intermediate frequency;

an IF-to-digital conversion circuit for receiving the OFDM/DMT transmissions at the intermediate frequency and converting the transmissions to the digital data.

11. A multi-point communications system as claimed in claim 9 wherein the second means comprises means for executing a Fourier Transform on the digital data.

12. A multi-point communications system as claimed in claim 9 wherein the second means comprises a correlator.

13. A multi-point communications system as claimed in claim 9 wherein the third means comprises an analog-to-digital converter disposed in the first means for converting the analog OFDM/DMT transmissions to the digital data at a sampling frequency which results in aliasing of the digital data characteristics thereby to reduce the number of digital data samples process by the second means.

14. A multi-point communications system as claimed in claim 9 wherein the third means comprises a band pass filter disposed in the first means for limiting the number of bins that are converted to generate the digital data to a subset of the first number of bins of the OFDM/DMT transmissions.

15. A multi-point communications system as claimed in claim 8 and further comprising decoding means for receiving the frequency, amplitude, and phase information from the second means and decoding the information to recover the communication data imposed on the OFDM/DMT signal by the transmitter at the primary site.

16. In a multi-point communications system having a receiver and transmitter disposed at a primary site for communication with a plurality of remote service units disposed at respective secondary sites, the transmitter of the primary site using OFDM/DMT transmissions over a first number of transmission bins to transmit communication data, a receiver for use in one or more remote service units comprising:

analog filter means receiving the first number of transmission bins at an input thereof and providing an analog signal at an output thereof corresponding to a second number of transmission bins, the second number of transmission bins being a subset of the first number of transmission bins and being provided at the output of the analog filter means to the exclusion of other bins in the first number of transmission bins;

an analog-to-digital converter circuit accepting the of the analog filter means and converting the analog OFDMIDMT transmissions of the second number of transmission bins into digital data; and

a digital data processing circuit connected to receive the digital data from the analog-to-digital converter circuit for processing the digital data corresponding to the second number of transmission bins to extract frequency, amplitude, and phase information from the digital data.

17. A receiver as claimed in claim 16 and further comprising a decoder to extract digital data communication intelligence from the frequency, amplitude, and phase information of the digital data output of the digital data processing circuit.

18. A receiver as claimed in claim 16 wherein the analog filter means comprises: a tuner circuit having an input and an output;

an IF converter circuit having an input accepting a signal processed by the tuner circuit; and

a bandpass filter accepting an input signal processed by the IF converter and providing an output signal for subsequent processing by the analog-to-digital converter circuit.

19. In a multi-point communications system having a receiver and transmitter disposed at a primary site for communication with a plurality of remote service units disposed at respective secondary sites, the transmitter of the primary site using OFDM/DMT transmissions over a first number of transmission bins to transmit communication data, a method of extracting intelligent data from the first number of transmission bins comprising the steps of:

receiving the first number of transmission bins at a receiver of the remote service unit;

digitally processing a second number of transmission bins at the receiver to extract frequency, amplitude, and phase characteristics of signals in the second number of bins, the second number of transmission bins being a subset of the first number of transmission bins, the second number of transmission bins being digitally processed to the exclusion of other bins of the first number of transmission bins.

20. A method as claimed in claim 19 and further comprising the step of:

decoding the digitally processed data to extract digital data communication intelligence from the frequency, amplitude, and phase information of the digital data output of the digital data processing circuit.

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UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 5,790,514
DATED : August 4, 1998
INVENTOR(S) : D. Marchok, R. Younce, P. Melsa

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown bel

Claim 8, column 14, paragraph a,
Line 59, the phrase "OFDMIDMT" should read -- OFDM/DMT --.

Claims 16, column 16,
Lines 11-12, the phrase "OFDMIDMT" should read -- OFDM/DMT --.

Signed and Sealed this

Eighteenth Day of September, 2001

Attest:

Nicholas P. Godici

Attesting Officer

NICHOLAS P. GODICI
Acting Director of the United States Patent and Trademark Office